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Evidence for rapid evolution of periodic variations in an ultracool dwarf

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ABSTRACT

The results of three short photometric monitoring runs on the L0 dwarf 2MASS J06050196−2342270, during three consecutive nights, are presented. The observations show the persistent presence of a 2.4-h period, with an I_C band amplitude which decreased from 27 to 11 mmag over the three nights. The amplitude in the R_C band appeared to be substantially smaller than in the I_C band.

Key words: stars: low mass, brown dwarfs – stars: variables: other.

1 INTRODUCTION

Brief summaries of the literature on variability in stars and brown dwarfs of spectral types L and T were given in Koen (2003, 2004, 2005b). Both flares and slower modes of variability have been observed. The latter are usually ascribed to rotational brightness modulation, caused by spots on the surface of the objects. The most likely origin for such spots are magnetic activity, or variations in surface opacity ('weather' patterns) of the object (see e.g. Bailer-Jones & Mundt 2001; Martín, Zapatero & Lehto 2001; Gelino et al. 2002).

In a number of cases in which objects were found to be variable, further observations found either no variability or changes in the variability pattern [see the brief review in Koen (2003)]. Perhaps the most striking example is the case of the brown dwarf Kelu-1, in which Clarke, Tinney & Covey (2002) discovered a very low amplitude periodicity from time-series photometry. Although the same periodicity could be identified in later Hα measurements by Clarke, Tinney & Hodgkin (2003), simultaneous photometry showed only aperiodic variability.

Bailer-Jones & Mundt (2001), in their photometric study of 21 objects with spectral types M6–L5, found that aperiodic variations were more common than strictly periodic brightness changes. They ascribed this to rapid evolution of surface features (areas of inhomogeneous brightness). 'Rapid' here means a time-scale shorter than, or comparable to, the time spanned by their observations. The time coverage of targets given in their table 2 ranged from 29 to 126 h, with a mean of 71 h. Since 16–70 (average 33) measurements per target were obtained in a season, detailed conclusions were clearly not possible.

By contrast, periodicities persistent over times of several days, and with no apparent evolution, have been seen in some ultracool dwarfs (see e.g. Koen 2003, 2005a). The aim of the present paper is to shed further light on the time-scale of evolution of periodicities in a very cool star/brown dwarf.

A time-series photometric study of the dwarf 2MASS J06050196−22342270 (hereafter 2M 0605−22342) is presented below. This object was discovered to be ultracool by Cruz et al. (in preparation), who assigned the spectral classification L0. The object was observed continuously for 3–4 h on three consecutive nights. The measurements show clear evidence for a persistent periodicity, with a pronounced decline in amplitude over the three nights.

Data acquisition is described in Section 2. Results of frequency analyses are given in Section 3 and conclusions are presented in Section 4.

2 OBSERVATIONS AND REDUCTIONS

Observations in the R_C and I_C bands were made with the South African Astronomical Observatory (SAAO) CCD camera mounted on the SAAO 1.9-m telescope. The instrumental setup, observational technique and reduction procedure were exactly the same as that described in Koen (2003), to which the interested reader is referred.

A log of the observations is given in Table 1. On two nights (2005 December 2/3 and 4/5), alternate short exposures were made through the two filters, over the course of a few hours, while one night (2005 December 3/4) was devoted to intensive monitoring in the I_C band alone.

A short description of the rough standardization of the photometry follows. The R magnitudes of the two brightest stars in the field of view of the camera were extracted from the Guide Star Catalogue; the difference $\Delta R = 0.56$ mag between the two values agrees quite well with the $\Delta R_C = 0.51$ mag mean difference measured at SAAO. Similarly, the difference between the I magnitudes in the USNO-B1.0 catalogue is 0.62 mag, while the mean SAAO difference is $\Delta I_C = 0.57$ mag. Zero points were therefore set by equating the mean measurements for the brightest star to its catalogue entries. The resulting mean magnitudes of 2M 0605−22342 were then $R_C = 19.98$ and $I_C = 17.23$; the USNO-B1.0 entries are $R = 19.22$ and $I = 17.76$, which are at least qualitatively similar. The two-micron All-Sky Survey (2MASS) near infrared magnitudes are $J = 14.51$, $H = 13.73$ and $K = 13.15$.

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Table 1. The observing log.

Filter	Starting time (HJD 247 3700+)	Run length (h)	Exposure time (s)	N	σ (mmag)
I_C	7.4516	3.3	90, 100	33	21
R_C			220, 240	28	41
I_C	8.4337	3.8	120	97	17
I_C	9.4083	4.3	100	37	18
R_C			250	36	32

The time-series of observations are plotted in Figs 1 (I_C filter) and 2 (R_C filter). In both the cases, measurements of two other stars in the field of view are also shown in order to convey an impression of the quality of the photometry.

3 FREQUENCY ANALYSIS

The amplitude spectra of the three I_C band runs are shown in Fig. 3. The trend in the data from the third night (HJD 245 3709) was removed by fitting a low-frequency ($f = 4.37$ d^{-1}) sinusoid, and then subtracting it from the data. (This was done to remove an excess of low-frequency power, in order to highlight features at higher frequencies). A variation near 10 d^{-1} is clearly present during all three runs, with an amplitude which decreased over time. Since in all the three runs the ratio of run length to period is not much larger than 1, the frequency resolution of the spectra in Fig. 3 is quite poor.

A rough significance level for the modest-looking peak in the bottom panel of the figure can be calculated using the well-known result for Gaussian white noise with variance σ^2; the scaled periodogram $2I(\omega)/\sigma^2$ has a χ^2 distribution with two degrees of freedom (e.g. Chatfield 2004). Symbolically,

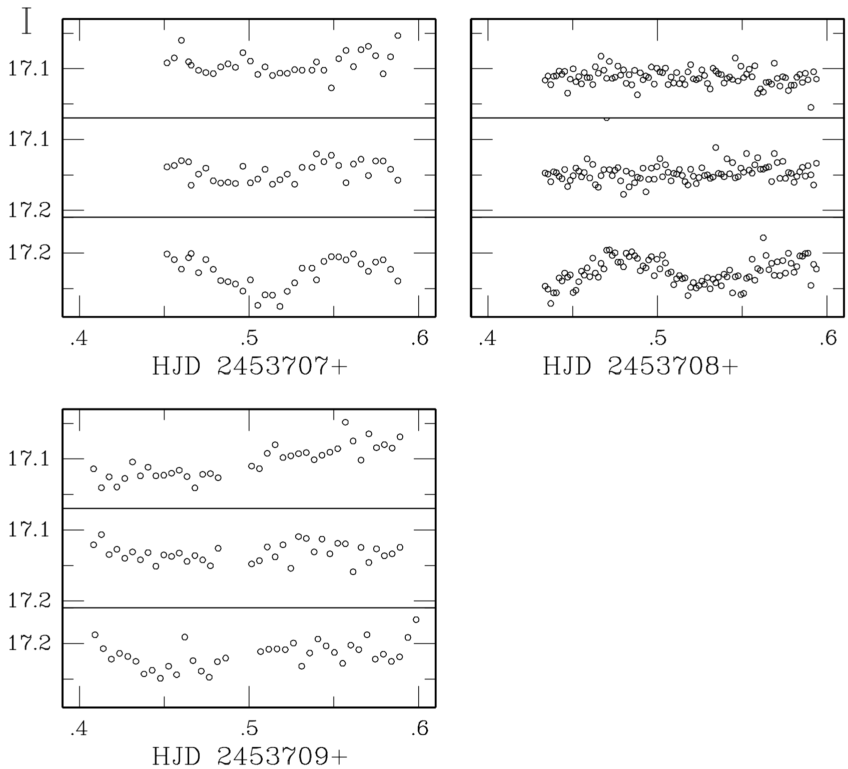

Figure 1. I_C-band observations of 2M 0605−22342 (bottom panels) and two other stars (of similar brightness) in the field of view. The vertical scale on all axes is 0.14 mag.

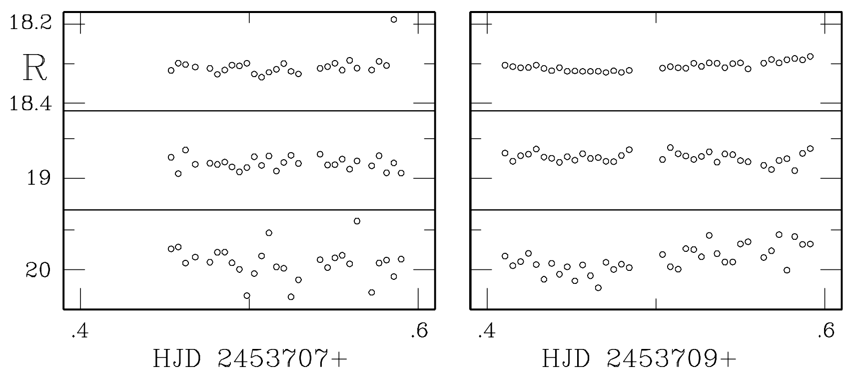

Figure 2. R_C-band observations of 2M 0605−22342 (bottom panels) and two other stars in the field of view. The vertical scale on all axes is 0.25 mag.

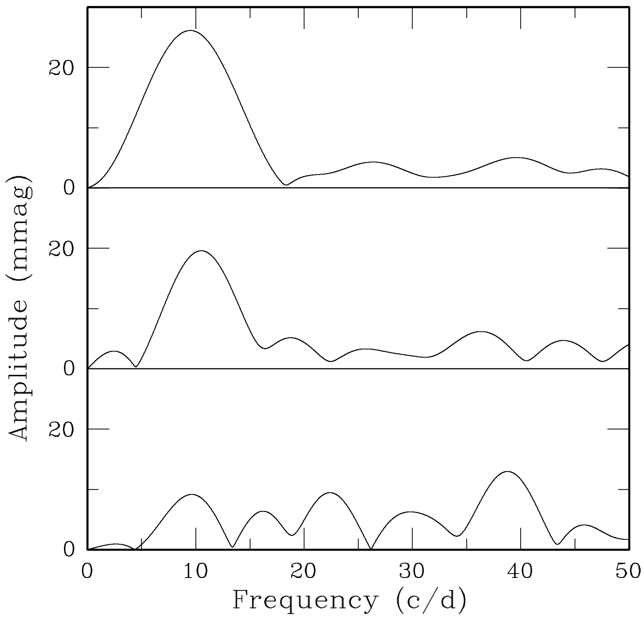

Figure 3. Amplitude spectra of the three sets of I_C-band observations. The data from the third night were pre-whitened by a low-frequency sinusoid before the plotted spectrum was calculated.

$$\frac{2}{\sigma^2} I(\omega) = \frac{N}{2\sigma^2} S^2(\omega) \sim \chi^2_2,$$

where $S(\omega)$ is the amplitude spectrum, N is the sample size and ω denotes frequency. In the present case, $S(2\,\pi \times 9.6) = 11$ mmag, $N = 37$ and $\sigma = 16$ mmag (after detrending), giving a value of 8.7 for the statistic. The significance level is about 1.3 per cent, i.e. the peak is highly significant.

The analogous results for the two nights of R_C band measurements are plotted in Fig. 4. The data from the second night have again been pre-whitened (by subtracting a sinusoid with $f = 4.15$ d^{-1}). Features near 10 d^{-1} can again be seen in both spectra, albeit less obviously than in the I_C band.

The results of fitting sinusoids to the data (pre-whitened, as mentioned above, in the case of HJD 245 3709) are given in Table 2. The difference of 0.82 d^{-1} between the first and the second I_C band frequencies is rather large at first glance, but since the formal standard error is 0.46 d^{-1}, it is not significant. It may be concluded that the five frequencies in the table are compatible, whereas the amplitude clearly declines over time. It also appears likely that the R_C band amplitudes are lower than those seen through the I_C filter, but this cannot be stated with formal certainty.

Table 2. The results of fitting sinusoids to the individual runs. Formal standard errors are given in brackets.

Date	I_C filter		R_C filter	
(HJD)	Frequency (d^{-1})	Amplitude (mmag)	Frequency (d^{-1})	Amplitude (mmag)
245 3707	9.49 (0.35)	27 (2)	10.65 (2.3)	19 (10)
245 3708	10.31 (0.30)	18 (2)		
245 3709	9.63 (0.93)	11 (3)	9.81 (1.8)	9 (5)

Inspection of Fig. 1 shows that the mean I_C band magnitudes are very similar from night to night (mean magnitudes were 17.23, 17.23 and 17.22, respectively). The three data sets were therefore combined, and an overall amplitude spectrum calculated. The result can be seen in the top panel of Fig. 5. The best-fitting frequency (in the least-squares sense) is 9.78 d^{-1}, with a formal standard error of 0.02 d^{-1}, and an amplitude of 18 mmag. The standard error should be taken with a pinch of salt, given the clear aliasing in the spectrum. The amplitude spectrum of the residuals left after subtraction of the best-fitting sinusoid is plotted in the bottom panel of Fig. 5. Pre-whitening by a single frequency has obviously left little more power near 10 d^{-1} than contained in the general noise level.

The R_C band data are much noisier, and also more sparse, and hence the aliasing is much more severe. The formal standard error of 0.10 d^{-1} on the best-fitting frequency of 9.20 d^{-1} is therefore quoted only for completeness.

The frequency determination was repeated using the period finding method described by Koen (2003), which can accommodate changes in the mean brightness level from night to night. Given the small differences in measured mean magnitudes, it is not surprising that the results for the I_C band are very similar to those obtained above – $f = 9.80$ d^{-1}, with an amplitude of 19 mmag. For the R_C band data, the best-fitting frequency by this method is 11.34 d^{-1}.

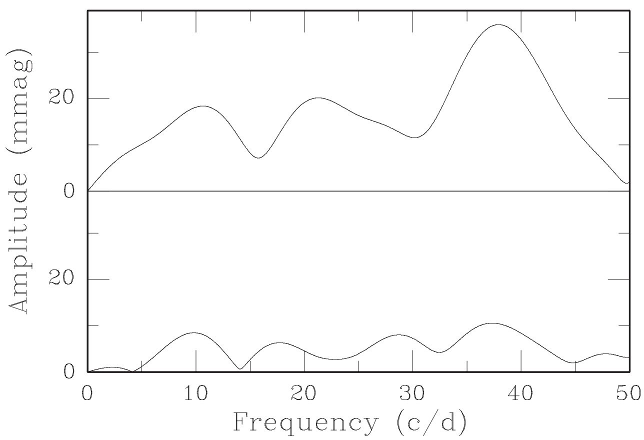

Figure 4. Amplitude spectra of the two sets of R_C-band observations. The data from the second night were pre-whitened by a low-frequency sinusoid before the plotted spectrum was calculated.

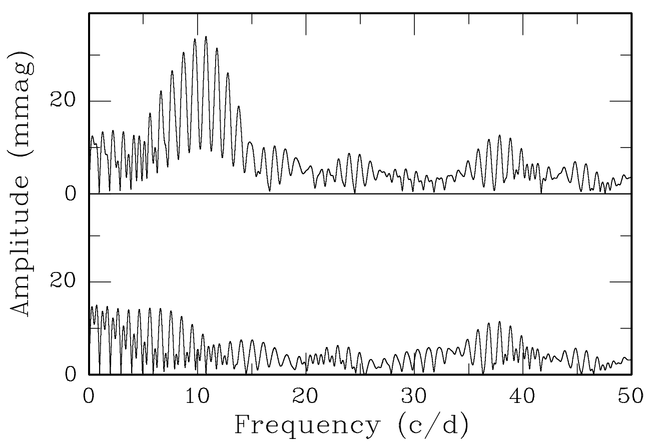

Figure 5. Amplitude spectra of the combined I_C-band observations (top panel). The bottom panel shows the residual amplitude spectrum after pre-whitening the combined data by the best-fitting sinusoid.

4 CONCLUSIONS

The analysis of Section 3 shows that the 2.4-h periodic variability in 2M 0605$-$22342 was persistent over the 3 days spanned by the monitoring, but the amplitude declined substantially. This clearly has implications for the understanding of variability in this object: if the amplitude changes are indeed due to the evolution of surface features, then either the area covered by spots or their temperature contrast changed markedly over some hours.

It also seems likely that the amplitude of the variations was smaller in the R_C band than in the I_C band.

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